SHAPE-CHANGING ARCHITECTURAL SYSTEMS: A Bottom-up and Top-down Approach for Developing Responsive Building Skins

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Abstract: In recent years, there has been an increasing interest in shape-changing smart materials in architectural research and practice. Research into responsive building skins with shape-changing materials has argued that the advantage of such systems relies on their potential for improved performance of buildings. However, few studies have proposed methods for developing responsive skins using shape-changing materials with the target of optimizing environmental performance. This paper discusses the methodological approach of a doctoral research agenda that aims to create a framework for developing a responsive shading system using shape-changing materials with the target of optimizing environmental performance. The methodology has two complementary approaches: a bottom-up study that deals with the development of shape-changing prototypes and top-down research that models the overall configuration of the responsive skin system. The paper discusses the two complementary approaches in terms of a case study.

Keywords: responsive skin, shape-changing materials, research methods, smart materials

INTRODUCTION

In recent years, there has been an increasing interest in smart materials in architectural research and practice. The development of novel materials in material science, chemistry, and other related fields has provided an entirely new material palette for designers (Addington and Schodek 2012). These include smart materials, from thermochromic materials that change visual appearance due to temperature changes to piezoelectric materials that present an electric response when mechanical stress is applied. Among these materials, shape-changing materials are characterized by presenting a strain that leads to a material transformation in response to a stimulus (i.e., water, heat, electricity). While there is an increasing number of studies that explore the development of architectural elements using these shape-changing materials, there has been little discussion of the strategies designers can use for efficiently incorporating these materials into architectural design.

On the other hand, in the current context of increasing environmental concern, a considerable amount of research has been directed at developing more efficient architectural skins. In fact, the envelope of a building is known to have a significant impact on environmental performance and thus accounts for a large portion of the total energy consumption of buildings (Echenagucia et al. 2015). Drawing inspiration from nature, a bio-inspired approach to research into building envelope design has adopted the term architectural skin (Velikov and Thun 2013) to name the barrier between inside and outside responsible for protecting, exchanging, and harvesting functions. Innovative architectural skin systems have started to emerge in the past decades using smart materials, and more specifically, shape-changing materials. Research into developing responsive architectural skins with shape-changing materials has argued that the advantage of such materials relies on the improved performance of buildings. However, few studies have proposed methods for developing responsive skins using shape-changing materials with the target of improving environmental performance. The question is, then;

1. *How can we develop a responsive skin using shape-changing materials with their inherent material properties and limitations?*
2. *How can environmental performance simulation inform the design of such a responsive skin system?*

These two research questions are causally interlinked and cannot be solved linearly. The work presented in this paper forms part of an ongoing doctoral research agenda aimed at developing computationally-enabled design and fabrication protocols for responsive skin systems using shape-changing materials that target improved environmental performance in buildings. This paper describes the overall methodological approach selected to address the two research questions mentioned above. The methodology has two complementary approaches: a bottom-up study that deals with the development of shape-changing skin prototypes, and a top-down study that models and proposes the overall configuration of a responsive skin system based on performance metrics. We show examples of the two complementary approaches by tracing the development of a responsive skin system fabricated by 3D printing with a hydro-active wood filament, as a case study.

The first section of this paper provides a brief overview of shape-changing smart materials and on the use of shape-changing materials for improved environmental performance. The next section presents the overall framework, describing the methodological approach proposed, and examples of implementing the framework with the case study of developing a responsive skin by 3D printing with hydro-active wood. Finally, the paper presents a discussion on the expected outcomes of this research.

1. BACKGROUND

The two research questions presented in the introduction require two different bodies of knowledge as the theoretical foundation of this research. The first relates to the bottom-up development of designs, based on a material-centered exploration. This research is concerned with proposing novel designs with materials typically developed outside the field. Therefore, these materials need to be experimented with to account for their properties, constraints, and affordances. The second group of studies relates to the use of shape-changing smart materials in the construction of building envelopes that optimize environmental performance. This section provides an overview of these two bodies of literature that frame this research.

1.1. SHAPE-CHANGING MATERIALS FOR IMPROVED ENVIRONMENTAL PERFORMANCE

Smart materials have long been in the research agenda of material scientists and engineers but have only recently begun to permeate design practice. Shape changing materials when affected by a stimulus -water, temperature, or other- present a strain that leads to shape change. A recent review (Vazquez, Randall, and Duarte 2019) has identified (hygroscopic) wood and Shape Memory Alloys as the two most common materials used for their shape-changing properties. The review has also indicated typical design and manufacturing patterns, extracted from a group of 44 studies (from 2007 to 2019). The extracted patterns indicate typical design solutions to developing responsive skin system with shape-changing materials, for instance, the combination with static materials or the use of shape-changing materials as the skin or the actuator. The patterns also capture common manufacturing strategies across the studies, showing how researchers have constructed shape-changing actuators. Furthermore, the review highlighted the lack of studies that incorporate building performance simulations to shape the design of such responsive skins. Remarkably, one of the main arguments for the incorporation of such materials into architectural practice relies on the promise of improved environmental performance. Nevertheless, this area remains widely unexplored.

There are several types of skin or envelope systems one could select to enhance environmental performance in buildings. Figure 1 illustrates three different approaches. Perhaps the most well-known relies on optimizing a skin system by selecting the 'overall best' design solution. This approach can be seen in the work by (Vazquez, Poerschke, and Duarte 2020), where an optimal brick configuration is selected for a shading masonry screen wall, considering yearly values of daylight and energy performance. A drawback of this approach is that the design optimization ocurrs before construction; therefore, it does not account for fluctuating environmental conditions throughout the year or even varying conditions on the environment—such as new surrounding buildings—that change the exposure of buildings to the sun. This first type of skin solution for improved environmental performance is a *static system*. The second approach relies on the use of mechanical systems to construct responsive skins that adjust their configuration to respond to shifting environmental conditions. With this approach, the skin can adopt the most favorable configuration according to the environmental conditions, thereby improving environmental performance. This second type of system can be seen in the responsive skylight by Castro Henriques (2012 Engineering and Construction (AEC). The high maintenance and material cost of such mechanical systems is perhaps the most significant disadvantage of these types of envelopes. This second approach can be characterized as a *dynamic system*. There is a third approach that is enabled by shape-changing smart materials, a responsive system where these materials replace expensive systems and are designed to adjust their configuration in response to changes in the environment.

This research targets the creation of a shape-changing system that can improve environmental performance in buildings, aligned with the third approach described as a responsive system. The ability to dynamically adjust to shifting environmental conditions without costly mechanical systems by using shape-changing smart materials is, without a doubt, a promising area of inquiry. The embedded sensor and actuation technologies of shape-changing materials enables designers and researchers to envision novel systems that can help improve the environmental performance of buildings.

Figure 1: Different types of skin systems for enhancing environmental performance in buildings. (Author 2020)

1.2. MATERIAL-CENTERED EXPLORATIONS

On the other hand, this research also seeks to find ways to achieve optimal design configurations using shape-changing materials, understanding their inherent material properties and limitations. Designing with shape-changing materials presents several challenges since they are inherently dynamic, which challenges one to design with the 4th dimension of time (Kennedy 2012; Vazquez and Duarte 2019). Another critical issue of designing with smart materials is how to combine them with existing building systems, and how to understand their affordances and limitations beyond mere replacement of current building structures (Kretzer 2014). Consequently, the development of responsive architectural skins using shape-changing material is highly experimental and requires iterative cycles of design, fabrication, and testing. This research adopts an experimental model of inquiry, where the development of prototypes and subsequent testing informs the construction of a design system.

This research is aligned with the emergence, in digital design culture, of a material-centered approach, which favors experimental models of research. Ahlquist et al. 2013, for instance, argues that a framework for computational thinking is critical for enabling research into a material system where there is a sequence of experimentations in increasing levels of complexity. The framework proposed by the author seeks to integrate material properties as design generators, where digital techniques enhance the integration of form and structure within the logic of manufacturing technologies (R. Oxman 2012). The model opposes the dominant epistemological frameworks in design that usually rely on final products rather than processes of material formation, as described in work by (Gürsoy and Özkar 2015). By adopting such an approach, the goal is to develop systems where the properties of shape-changing materials are not a foreground of their application (Addington 2010) or 'patched atop' existing technologies (N. Oxman 2010), but instead, their properties give form to efficient and responsive systems.

Research into shape-changing materials -and new materials, in general, has already adopted such experimental models of inquiry. The presence of an iterative cycle of development and testing can be traced in the work of several studies on shape-changing materials in architecture. For instance, Yoon (2019) argues that he conducts his research into Shape Memory Polymers for thermal-responsive facades through intuitively proposing design solutions and verifying them through fabrication and digital simulation. Similarly, Khoo et al. (2011) propose three design experiments in developing morphing skins with Shape Memory Alloys and develop prototypes to test and suggest new architectural design ideas. The introduction of shape-changing materials in architectural design is at its early stages. Therefore, most studies adopt an experimental approach going through incremental cycles where computational tools and methods aid the process. Furthermore, the dynamic behavior of the shape-changing materials is usually not known in advance to researchers, since in most cases, these materials are constructed -for example, through bi-layers or 3D printing. Therefore, a systematic and experimental approach helps understand the embedded material intelligence of these materials to incorporate them into responsive systems.

2. RESEARCH APPROACH

2.1. THE CASE STUDY: DEVELOPING A RESPONSIVE 3D PRINTED HYGROSCOPIC SKIN

This research adopts the form of a case study detailed in this section. While this paper focuses mainly on presenting the research methods, a brief background on the problem and the current state is necessary to contextualize the discussion. The case study proposed is the development of a responsive architectural skin fabricated through 3D printing with a hygroscopic wood-based filament, that could potentially improve daylight conditions indoors. The two research questions refer to, on one hand, proposing a design system for improved environmental performance, and on the other, developing such a system using a shape-changing material with its inherent properties and limitations. To explore the potential design configurations with the shape-changing material, one must adopt the bottom-up approach. To propose and optimize such configurations, one must adopt a top-down approach. The methods section details these parallel and complementary courses of action.

As mentioned before, this research started with a systematic review of the literature, which identified typical design and manufacturing patterns among the body of literature on shape-changing materials used for responsive building envelopes. The review also identified the need for developing responsive building skins, taking into consideration environmental performance factors. Following the review, the first explorations in this research project aimed to study the constraints and affordances of the material by developing initial manufacturing digital protocols for 3D printing and, thereafter, characterizing its hydro-active behavior. Relevant references of this study were the 3D printed responsive systems by Correa et al. (2015) and Correa and Menges (2017). In the studies, the authors presented methods for designing hydro-active wood structures by 3D printing, controlling the alignment of wood fibers through toolpath design.

Building upon this existing body of work, the first set of outcomes of our experimental study was formalized into rules in (Vazquez, Gürsoy, and Duarte 2020). The rules depict the lessons learned from toolpath design, shape-change and how to capture it, and design principles for shape-changing kirigami geometries. The next step of this research is to speculate on the form of a large-scale skin system and construct a full-size physical model, to assess the material limitations and deal with scalability issues.

2.2. THE RESEARCH FRAMEWORK

This section details the methodological approach adopted in this doctoral research aimed at developing a responsive skin using shape-changing materials for improved environmental performance in buildings. The first section describes the overall framework for addressing the research question in two complementary approaches. The second section moves on to describing the specific model utilized for conducting the bottom-up section of the research. The methods and approaches are described in terms of the case study for developing a responsive skin system by 3D printing with a hydro-active wood filament.

This research is conducted in two different and complementary approaches. The general methodology proposed to address these two research questions is illustrated in figure 2. As mentioned before, there are two complementary approaches involved. (1) A bottom-up approach that is concerned with prototyping the testing manufacturing strategies for a shape-changing system and (2) a top-down approach that deals with defining the overall geometry of the responsive skin system, focused on improved daylight performance. The two types of research are developed in iterative cycles of development and testing, going from manufacturing to the overall design, and vice versa. The cycle cannot be linear because novel design possibilities emerge from exploring and thinking with the material. At the same time, developing a design system for the overall configuration helps inform material explorations at a smaller scale, and provides parameters (shape, size) to the smaller scale.

The graphic also exemplifies what kind of studies are developed on each scale. In the smaller-scale work of the bottom-up studies, the research addresses the development of manufacturing strategies. The work conducted in this approach is aimed at formalizing strategies for embedding and programming responsiveness through manufacturing processes in this research by 3D printing. In the case study, these strategies refer to, for instance, defining toolpath configurations, studying how to construct bi-layered systems with differential swelling. Similarly, studies at the micro-scale of toolpath design are combined with studies at the mesoscale of geometrical configurations. In the case study, for instance, we studied how kirigami geometries deform when a stress is applied and see if we could replicate those transformations with toolpath design. To achieve this, we divided complex kirigami geometries into bending with opposite directions (concave and convex curvatures).

At the larger scale of the top-down approach, there is an interest in thinking about what could be suitable design configurations for shape-changing skins. This approach is, in a sense, more speculative. Nevertheless, it informs the bottom-up explorations by providing a goal and a direction to the studies. At this scale, digital simulation methods also inform the process by providing feedback on the desired performance of the skin systems. Namely, rough and early performance analysis can help inform the definition of initial configurations for the responsive system. Figure 3 shows a parametric definition of a responsive façade using kirigami geometries as the basic shape-changing module.

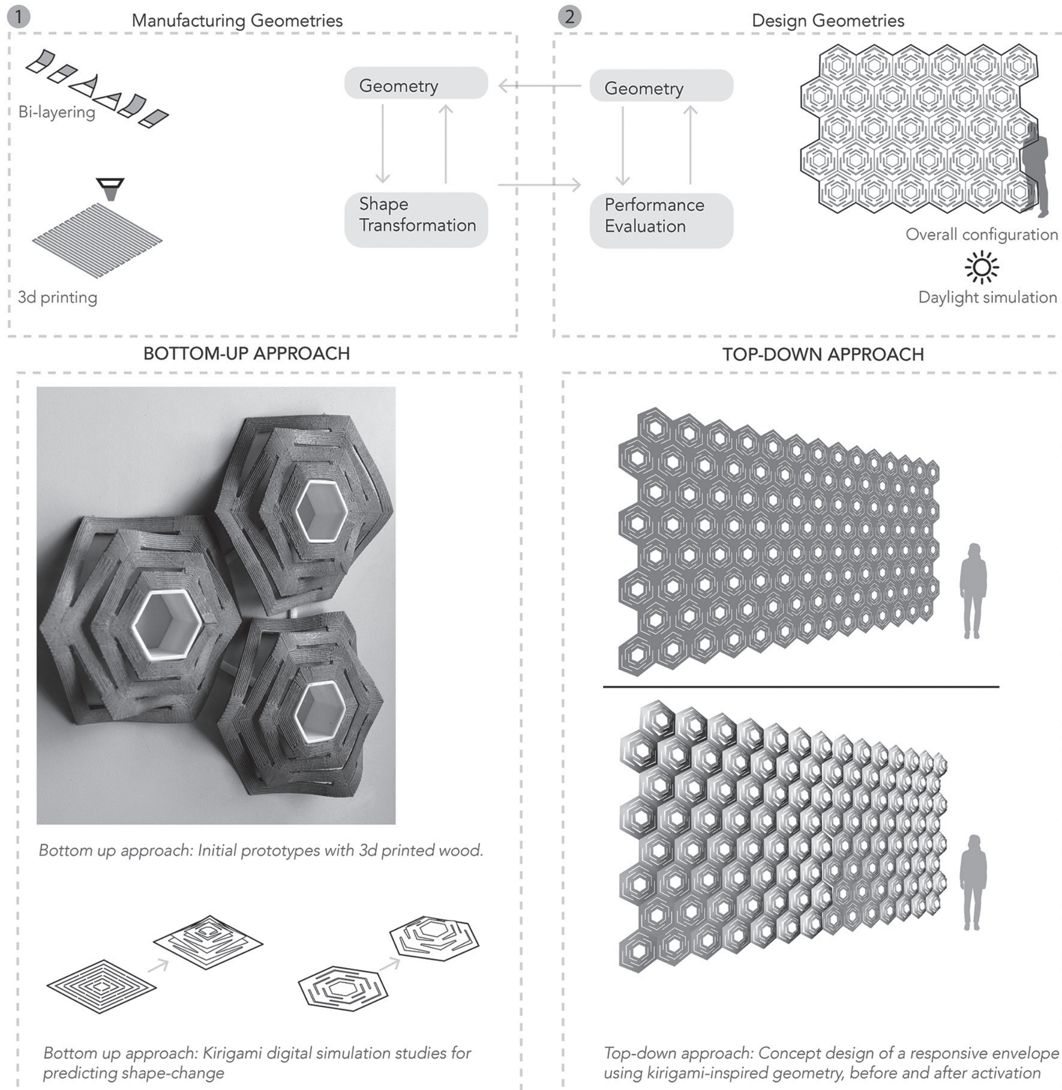

Figure 2: The general research framework. (Author 2019)

On the other hand, due to the lack of practical methodologies for material-centered explorations, we defined a model to guide this bottom-up iterative cycle of development and testing. Figure 3 illustrates the experimental model adopted of development and testing with shape-changing materials adapted from (Vazquez, Gürsoy, and Duarte 2020). The process begins by defining a framework for material exploration, which identifies the material/process/design/actuation variables that define the prototypes. For instance, when 3D printing responsive hygroscopic materials with wood-based filaments, the framework includes four types of variables. One, which filament is used (material variables), two, what printer and settings will be used to fabricate the responsive structures (process variables), three what geometric configurations will the printed parts have (design variables), and four, what are the actuation conditions (activation variables) to be tested—for instance, relative humidity %. The next step is to perform a material exploration by systematically changing one variable at a time, to asses which settings perform best for the design purposes. Finally, the findings of this exploration are formalized through rules, computer algorithms, text descriptions, design patterns, or others. These findings also inform the next cycles of the process. The cycle of development and testing is a cycle of abstraction and materialization. For a more detailed explanation of the model for bottom-up explorations, readers can refer to (Vazquez, Gürsoy, and Duarte 2020)

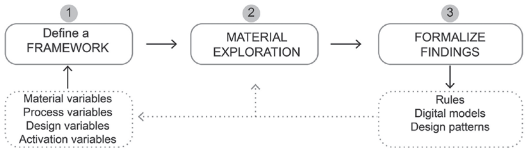

Figure 3: The model for bottom-up explorations. (E. Vazquez, Gürsoy, and Duarte 2019)

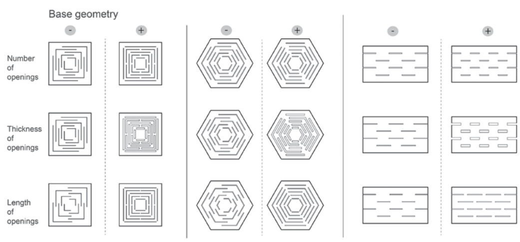

Figure 4: A design matrix for possible kirigami geometrical configurations. (Author 2019)

The initial framework for material-centered explorations can be based on a single type of variable, such as design variables. In the case study of 3D printing with a responsive wood filament, we were concerned with exploring the use of kirigami-inspired geometries for amplifying the shape-transformation of the prototypes. Consequently, after an initial testing in which we defined appropriate printing settings, we moved on to develop a second set of explorations based on a framework that considered mostly design variables. Therefore, we defined a design matrix for possible geometric configurations selecting different design variables that define such geometries. Figure 4 depicts the matrix developed that includes design variables such as number of openings, thickness of openings, and length of openings. From this matrix, we selected some geometries, and performed a material exploration to see how the different design variables conditioned the shape-changing response of the prototypes to humidity.

2.3. EXPECTED OUTCOMES

Having described the research framework, this section describes the expected outcomes of this research. Figure 5 depicts the general workflow of this study. The theoretical background, together with the extracted design and fabrication patterns done with the review, form the starting point of this research. The case study of developing a shape-changing architectural skin is done in increasing levels of complexity, through bottom-up and top-down studies as described in the previous section of this paper. The two complementary studies are developed through cycles of abstraction and materialization, where we go from digital-abstract

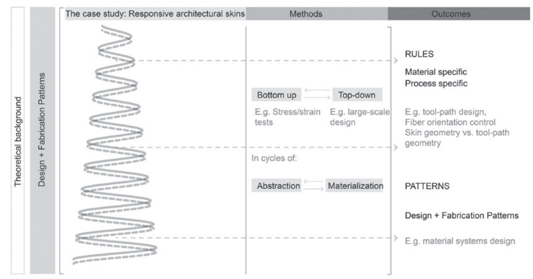

Figure 5: Research workflow. (Author 2019)

representations to materializing them. Finally, the two types of outcomes: rules and patterns, complete the process. These rules and patterns are intended to inform future research into designing and fabricating shape-changing architectural skins.

The outcomes of this research can be defined in terms of two levels. The first level is a series of rules that describe the interrelationship between material geometry, properties, and shape-changing behavior. These rules formalize material behavior and provide useful insights for the future development of responsive systems. For the most part, these rules are process-specific or material-specific. For instance, a set of rules defines the toolpath design, and a set of rules describes the shape-transformation. The theoretical support for the development of such rules will rely heavily on the shape grammar formalism. The grammar formalism is used to describe the material processes of making. Examples of this type of outcomes appear in (Vazquez, Gürsoy, and Duarte 2020), were we present rules for toolpath definition, rules for shape-change, and rules for defining kirigami geometries. While in some cases, these types of rules could be applied to other materials, this category of research outcomes is thought to be more process-specific and material-specific, since they do not have the flexibility attributed to the second type of research outcomes, patterns.

The second type of outcome is patterns. Patterns are understood in this context as "a solution to a problem in a recurring context" (Alexander 1977). In design science literature, patterns have been identified as more flexible and generalizable than rules that describe a technique for solving a class or type of problem (Vaishnavi and Kuechler 2015). Patterns also are defined as a "formalized way of recording experience" (Vaishnavi and Kuechler 2015, 2). In the context of this research, design patterns will describe generalizable techniques for designing shape-changing skin systems. Recall that one of the first steps of this research was to conduct an extensive literature review, where different design and fabrication patterns where extracted from the body of research into responsive

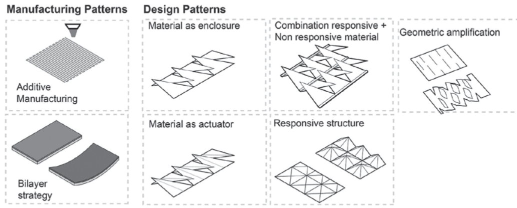

Figure 6: A summary of design and manufacturing patterns. (Author 2019)

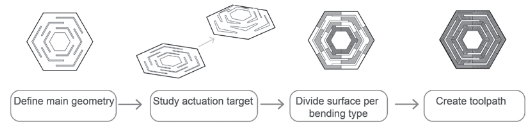

Figure 7: Proposed strategy for toolpath definition of shape-changing kirigami prototypes. Author 2019)

skins -a summary of them illustrated in figure 6. This first set of patterns inform this study in framing the existing alternatives for shape-changing materials and design solutions for skin systems. The outcomes of this research will also be formalized as patterns. These will be both graphics responding to our visual culture as architects and designers and in text. The goal is that such patterns will be flexible enough to inform research into designing dynamic architectures in general, and skin systems with different materials in particular.

An example of a design pattern that already emerged from this research are strategies for using kirigami geometries combined with 3D printing to develop shape-changing modules that can be used in a responsive architectural skin. Figure 7 summarizes the proposed strategy for toolpath definition of a kirigami-inspired responsive system. The process starts with defining the main kirigami geometry, which can be selected from the design matrix shown in figure 4. A second step is to study the actuation target through paper mockups or digital simulation. This study would allow us to characterize the shape-changing transformation, and divide the surface as per bending type. The process finishes with the definition of toolpath with corresponding active layers that swell perpendicular to the longitudinal direction of the area, and constraint layers, printed parallel to the long side of the area.

In summary, the outcome of this research will be formalized using rules and patterns. Rules are generally considered stricter and, therefore, will be mostly material-process-fabrication specific. On the other hand, patterns are more flexible and therefore complement and enhance the rules. These patterns will refer to design and manufacturing strategies and will be formalized visually and through descriptions. These patterns are intended to inform research using other shape-changing materials.

CONCLUSION

Shape-changing materials have the potential of conforming truly responsive environments that adjust their configuration according to the surrounding conditions. The increasing development of novel materials has allowed us, architects, to envision such spaces. The research presented is aligned with a research agenda intended at developing an efficient and responsive architectural skin system. This paper discusses the methodological approach adopted in a doctoral research agenda aimed at proposing methods for developing responsive skins using shape-changing materials with the target of optimizing environmental performance.

The methods discussed include two complementary approaches: a bottom-up strategy that aims to formalize fabrication strategies for achieving desirable design configurations and a top-down strategy that is concerned with studying and proposing an overall skin configuration for dynamically improving environmental performance. This research is conducted through iterative cycles of development and testing, jumping in between these two scales, where the findings of one scale inform the other and vice versa. Discussing examples of these two approaches, this article offers a reflective account of methods for design research in the new area of shape-changing materials.

This paper also discussed the expected outcomes of this study and its significance in the context of shape-changing architectural systems. Research into the potentials of shape-changing materials in architecture and design fields is in its early stages, being largely speculative yet visionary. Nevertheless, it is essential to formalize the design strategies for incorporating such materials into architectural elements, since such materials are inherently dynamic and conceptually different than traditional materials in architecture. These strategies go from how to synthesize material behavior to how to give them shape with digital fabrication methods. The outcomes of this research—defined as rules and patterns—intend to contribute to the discussion of how to incorporate shape-changing materials into design and research.

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